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4. Title of the invention	OPTICAL PROJECTION SYSTEM FOR PHOTOLITHOGRAPHY	
5. Name of your agent *(if you have one)* "Address for service" in the United Kingdom to which all correspondence should be sent *(including the postcode)* Patents ADP number *(if you know it)*	Stephen J. Avery Hoffmann Eitle European Patent Attorneys Sardinia House 52 Lincoln's Inn Fields London WC2A 3LZ 07156466001	

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Optical Projection System for Photolithography

The present invention relates to optical projection systems such as systems for photolithography.

In the following the term "anastigmat" means an optical element or group of optical elements adapted to reduce aberrations including spherical aberration. The term "Mangin mirror arrangement" means an optical device comprising a concave mirror and at least one negative powered lens proximal to the concave mirror wherein the concave mirror need not be in contact with the negative powered lens.

Historically, resolution in microlithography has been improved either by increasing Numerical Aperture (NA), or by reducing the wavelength of illumination light, or a combination of the two.

The theoretical resolution improvement of liquid-immersion is well known in microscopy, where oil-immersion dioptric objectives have for many years been designed with NAs greater than 1.0, but covering only a very small field of 0.5 mm or less. See, for example: "Modern Optical Engineering", by Warren Smith, Third Edition, page 450, published by SPIE Press and McGraw Hill.

Liquid immersion applied to microlithography has also been proposed for many years, but has been slow to be adopted in production, no doubt because of practical concerns. However, the theoretical advantages become stronger as "dry" projection lens NAs approach the theoretical limit of 1.0. These advantages have been described in, for example: "The k3 coefficient in nonparaxial λ/NA scaling equations for resolution, depth of focus, and immersion lithography" by Burn J. Lin published in JM3 1(1) 7-12 April 2002.

More recent investigations into the practical issues of liquid immersion for lithography have also become more optimistic, for example: "Resolution enhancement of 157 nm lithography by liquid immersion" by M. Switkes and M. Rothschild, published in JM3 1(3) 225-228 October 2002. However, neither of these papers addresses the issues of optical design.

Early papers proposing liquid immersion lithography include: "Optical projection lithography using lenses with numerical apertures greater than unity" by H. Kawata, J.M. Carter, A. Yen and H.I. Smith, published in Microelectronic, Eng. 9, 31~1989; "Fabrication of 0.2μm fine patterns using optical projection lithography

with an oil immersion lens" by H. Kawata, I. Matsumura, H. Yoshida and K. Murata, published in Japan, Journal of applied physics, Part 131, 4174~1992; "1/8 μm optical lithography" by G. Owen, R.F.W. Pease, D.A. Markle, A. Grenville, R.L. Hsieh, R. von Bunau and N.I. Maluf, in the Journal of Vacuum Science Technology, B10-6, 3032~1992; and "Immersion lithography at 157 nm" by M. Switkes and M. Rothschild, in the Journal of Vacuum Science Technology, B19-6, 2353~2001.

The recent Switkes paper is the most significant, in that it proposes the use of water as the immersion liquid for ArF (or KrF), perfluoropolyethers for F2, and starts to address the practical issues involved with a scanning wafer stage.

Another recent paper has started to address optical design issues for the relatively wide field of views used in lithography, partially disclosing liquid immersion dioptric microlithographic projection lens designs with NAs of greater than 1.0: "Development of dioptric projection lenses for DUV lithography" [4832-18] by Ulrich Wilhelm, Rostalski Hans-Juergen, Hudyma Russell M, published in SPIE Vol. 4832 IODC June 2002.

US 2001/0040722 A1 describes a catadioptric design which uses a V-fold mirror and two intermediate images. However, this is a small-field system (< 1 mm), specifically intended for optical inspection, and there is no indication that the design could be applied to the much larger field sizes and extremely small residual aberrations and distortion required for microlithography.

"High numerical aperture lithographic imagery at the Brewster angle" by Timothy A. Brunner et al in, JM3 1(3) 188-196, October 2002, describes the fundamental disadvantages in terms of image quality, as the NA approaches 1.0 in a "dry" projection lens. These relate to vector imaging degradation that is made worse by Fresnel reflection losses at the resist interface, which more strongly reflects and loses the polarization orientation that would have given the better image quality inside the photoresist. This occurs most strongly at Brewster's Angle, which corresponds to a NA of about 0.85.

NRCA has investigated liquid immersion dioptric designs, and has found that for a NA of 1.0 and 26 mm field size the largest lens diameters need to be of the order of 330 mm, which is on the limit of available high quality fused silica, and beyond the limit for calcium fluoride. There is also a reduction in spectral bandwidth, in the same way that there is for "dry" dioptric lenses as the NA increases. A reduction in field size and an increase in reduction ratio above 4x would help these issues, but would make the "wet" lithography tools incompatible with current "dry" systems.

Known "dry" catadioptric designs have relatively small lens diameters and chromatic aberrations. However, they cannot be converted to liquid immersion only by adding a liquid to the space between the last element and the wafer. This would introduce a large amount of spherical aberration, which has to be compensated elsewhere in the design. Also, in simply adding a liquid, the NA does not increase, since the definition of NA already includes the refractive index.

Immersing the wafer in liquid is a necessary, but not sufficient, condition for being able to increase the NA up to the theoretical maximum equal to the liquid refractive index (~ 1.4), rather than 1.0 in a "dry" system. For a constant magnification, paraxial Geometrical Optics theory (in particular, the Lagrange Invariant) dictates that an increase of NA at the wafer has to be accompanied by a corresponding increase in NA all the way through the projection lens system. This results in an increase in lens diameters, and optical surface steepness, defined by the ratio D/R, where D is the clear aperture diameter and R is the radius of curvature. At the same time, chromatic and high-order aberrations increase rapidly with NA.

It is therefore not obvious to one skilled in the art of optical design that the NA of a "dry" projection lens can be increased in the ratio of the refractive index of the immersion liquid, without both an impractical increase in the lens size and complexity, as well as an unacceptable increase in residual aberrations.

Textbooks on optical design (e.g. Warren Smith, Modern Optical Engineering Third Edition, page 449-450, published by SPIE Press and McGraw Hill) describe the historical microscope immersion objective with a hyper-hemispherical convex surface (clear diameter/radius of curvature beyond hemispherical, where D/R = 2) on the last element, opposite the plane surface in contact with the immersion liquid. Classically, this surface is designed to be either aplanatic, or close to the aplanatic condition. At the aplanatic condition there is zero spherical aberration, coma and astigmatism, and the marginal ray convergence angle is greater inside the lens element than before it by the ratio of the glass refractive index. Being close to this aplanatic condition minimizes spherical aberration and coma, and is a simple way of increasing NA, which is useful for a small field microscope objective, or systems such as the prior art US Patent Application US 2001/0040722.

For microlithography, which requires small aberrations over a much larger field size of many mm, such an aplanatic surface would give rise to higher-order aberration variations across the field, including oblique spherical aberration and coma. It is common practice to use, instead, a convex surface on this last element that is not at

the aplanatic condition, but rather at or near the so-called concentric, or monocentric condition. In the concentric situation the marginal ray convergence angle inside the last element is identical to that incident upon it. Again there is zero spherical aberration and coma, but more importantly for a wide-field system there is zero sagittal oblique spherical aberration. See, for example, J. Dyson, JOSA, volume 49(7), p. 713 (July 1959), or, "Monocentric telescopes for microlithography" by C.G. Wynne, Optical Engineering, Vol. 26 No. 4, 1987.

According to one aspect of the invention there is provided an optical system for projecting an image onto an image plane comprising: a boundary lens; and at least one layer of immersion liquid between the boundary lens and the image plane; said boundary lens having an optical surface shaped such that for light projected onto the image plane through the boundary lens the marginal ray convergence angle prior to incidence is larger than the marginal ray convergence angle within said boundary lens.

According to another aspect of the invention there is provided an optical projection system for projecting from an object plane to an image plane comprising: an optical system; a boundary lens; and at least one layer of immersion liquid between said boundary lens and said image plane; wherein light from the object plane is transmitted through the optical system, and output with a predetermined marginal ray convergence angle; and said boundary lens is positioned to receive said light output from the optical system, and adapted such that for light projected onto the image plane through the boundary lens the marginal ray convergence angle prior to incidence is larger than the marginal ray convergence angle within said boundary lens.

The optical system (which means the optical system of the optical projection system, where the former is included in an optical projection system) may further comprise at least one positive powered lens element proximal to said boundary lens, and having an aspheric optical surface.

Alternatively, the optical system may further comprise a first positive powered lens element proximal to said boundary lens, and having at least one aspheric optical surface, and a second positive powered lens element between the first positive powered lens element and said boundary lens, and having at least one aspheric optical surface.

The optical system may be one in which the first positive powered lens element has an axial thickness greater than 26.1mm and less than 28.9mm, and an object side surface with an axial radius of curvature greater than 103mm and less than 114mm, the second positive powered lens element has an axial thickness greater than 26.5mm and

less than 29.3mm, and an object side surface with an axial radius of curvature greater than 83.2mm and less than 91.9mm, and the boundary lens has an axial thickness greater than 41.6mm and less than 46.0mm, and an object side surface with an axial radius of curvature greater than 56.9mm and less than 62.9mm.

Instead, the optical system may comprise a first positive powered lens element proximal to said boundary lens, and having at least one aspheric optical surface, and a second positive powered lens element between the first positive powered lens element and said boundary lens, and having at least one aspheric optical surface, wherein the first positive powered lens element has an axial thickness greater than 27.22mm and less than 27.77mm, and an object side surface with an axial radius of curvature greater than 107.6mm and less than 109.8mm, the second positive powered lens element has an axial thickness greater than 27.63mm and less than 28.19mm, and an object side surface with an axial radius of curvature greater than 86.67mm and less than 88.42mm, and the boundary lens has an axial thickness greater than 43.37mm and less than 44.25mm, and an object side surface with an axial radius of curvature greater than 59.27mm and less than 60.46mm.

Any of the optical systems defined above may have a double-Gauss anastigmat arranged to reduce spherical aberration including a third positive powered lens element, a first negative powered lens element, a second negative powered lens element, and a fourth positive powered lens element.

In this optical system the third positive powered lens element has an axial thickness greater than 43.9mm and less than 48.5mm, and an object side surface with an axial radius of curvature greater than 128mm and less than 141mm, the first negative powered lens element has an axial thickness greater than 13.1mm and less than 11.9mm, and an object side surface with an axial radius of curvature greater than 1540mm and less than 1710mm, the second negative powered lens element has an axial thickness greater than 11.9mm and less than 13.1mm, and an object side surface with an axial radius of curvature greater than 184mm and less than 204mm, and the fourth positive powered lens element has an axial thickness greater than 30.6mm and less than 33.9mm, and an image side surface with an axial radius of curvature greater than 189mm and less than 209mm.

As an alternative to the optical system described in the preceding paragraph, the optical system may be one in which the third positive powered lens element has an axial thickness greater than 45.71mm and less than 46.63mm, and an object side surface with an axial radius of curvature greater than 133.3mm and less than

136.0mm, the first negative powered lens element has an axial thickness greater than 12.38mm and less than 12.63mm, and an object side surface with an axial radius of curvature greater than 1608mm and less than 1641mm, the second negative powered lens element has an axial thickness greater than 12.38mm and less than 12.63mm, and an object side surface with an axial radius of curvature greater than 191.9mm and less than 195.8mm, and the fourth positive powered lens element has an axial thickness greater than 31.91mm and less than 32.56mm, and an image side surface with an axial radius of curvature greater than 197.4mm and less than 201.3mm.

The optical system in any form as described above may comprise a catadioptric anastigmat comprising a concave mirror and at least one negative powered Shupmann lens.

In this optical system the catadioptric anastigmat can comprise two negative powered Shupmann lenses.

Any of the above optical systems may be adapted for use with ultraviolet light.

The optical system may comprise a set of optical elements substantially having the parameters as set out in Tables 1 and 2.

The optical system may comprise a set of optical elements having parameters substantially based on those in Tables 1 and 2, but adjusted to be re-optimised for a particular operating optical wavelength

According to a further aspect of the invention there is provided a method of projecting onto an image plane including the steps of passing light having a first marginal ray convergence angle to a boundary lens, passing light having a second marginal ray convergence angle though the boundary lens, and passing light from said boundary lens through a layer of immersion liquid to the image plane, wherein the first marginal ray convergence angle is greater than the second marginal ray convergence angle.

The method may include the step of passing light through at least one positive powered lens element proximal to said boundary lens, and having an aspheric optical surface.

Alternatively, the method may include the steps of passing light through a first positive powered lens element proximal to said boundary lens, and having at least one aspheric optical surface, and passing light through a second positive powered lens element between the first positive powered lens element and said boundary lens, and having at least one aspheric optical surface. This method may have the steps of passing light through a first positive powered lens element proximal to said boundary lens, and

having at least one aspheric optical surface, passing light through a second positive powered lens element between the first positive powered lens element and said boundary lens, and having at least one aspheric optical surface, passing light through the first positive powered lens element having an axial thickness greater than 26.1mm and less than 28.9mm, and an object side surface with an axial radius of curvature greater than 103mm and less than 114mm, passing light through the second positive powered lens element having an axial thickness greater than 26.5mm and less than 29.3mm, and an object side surface with an axial radius of curvature greater than 83.2mm and less than 91.9mm, and passing light through the boundary lens having an axial thickness greater than 41.6mm and less than 46.0mm, and an object side surface with an axial radius of curvature greater than 56.9mm and less than 62.9mm. Alternatively the method may include the steps of passing light through a first positive powered lens element proximal to said boundary lens, and having at least one aspheric optical surface, passing light through a second positive powered lens element between the first positive powered lens element and said boundary lens, and having at least one aspheric optical surface. passing light through the first positive powered lens element having an axial thickness greater than 27.22mm and less than 27.77mm, and an object side surface with an axial radius of curvature greater than 107.6mm and less than 109.8mm, passing light through the second positive powered lens element having an axial thickness greater than 27.63mm and less than 28.19mm, and an object side surface with an axial radius of curvature greater than 86.67mm and less than 88.42mm, and passing light through the boundary lens having an axial thickness greater than 43.37mm and less than 44.25mm, and an object side surface with an axial radius of curvature greater than 59.27mm and less than 60.46mm.

The methods as defined above may include the step of passing light through a double-Gauss anastigmat arranged to reduce spherical aberration including a third positive powered lens element, a first negative powered lens element, a second negative powered lens element, and a fourth positive powered lens element. Such methods may include the step of passing light through a double-Gauss anastigmat arranged to reduce spherical aberration including a third positive powered lens element having an axial thickness greater than 43.9mm and less than 48.5mm, and an object side surface with an axial radius of curvature greater than 128mm and less than 141mm, a first negative powered lens element having an axial thickness greater than 13.1mm and less than 11.9mm, and an object side surface with an axial radius of curvature greater than 1540mm and less than 1710mm, a second negative powered

lens element having an axial thickness greater than 13.1mm and less than 11.9mm, and an object side surface with an axial radius of curvature greater than 184mm and less than 204mm, and a fourth positive powered lens element has having axial thickness greater than 30.6mm and less than 33.9mm, and an image side surface with an axial radius of curvature greater than 189mm and less than 209mm. Instead the method may have the step of passing light through a double-Gauss anastigmat arranged to reduce spherical aberration including a third positive powered lens element having an axial thickness greater than 45.71mm and less than 46.63mm, and an object side surface with an axial radius of curvature greater than 133.3mm and less than 136.0mm, a first negative powered lens element having an axial thickness greater than 12.38mm and less than 12.63mm, and an object side surface with an axial radius of curvature greater than 1608mm and less than 1641mm, a second negative powered lens element has an axial thickness greater than 12.38mm and less than 12.63mm, and an object side surface with an axial radius of curvature greater than 191.9mm and less than 195.8mm, and a fourth positive powered lens element has an axial thickness greater than 31.91mm and less than 32.56mm, and an image side surface with an axial radius of curvature greater than 197.4mm and less than 201.3mm.

Any of the methods as defined above according to the third aspect of the invention may include the step of passing light through a catadioptric anastigmat comprising a concave mirror and at least one negative powered Shupmann lens, and this method may have the step of passing light through a catadioptric anastigmat comprising a concave mirror and two negative powered Shupmann lenses.

The light as used in the methods as defined above may be a beam of ultraviolet light.

The method may include the step of passing light through a set of optical elements having substantially the optical properties as set out in Tables 1 and 2.

The method may have the step of passing light through a set of optical elements substantially having optical properties based on those set out in Tables 1 and 2 but re-optimized for a particular operating wavelength.

The method may include the step of passing light through a set of optical elements substantially having optical properties based on those set out in Tables 1 and 2 but re-optimized for a particular operating wavelength and a particular immersion layer thickness.

For a better understanding of the invention, and to show how the same may be carried into effect, reference will now be made, by way of example, to the

accompanying drawings in which:

Fig. 1 shows an illustration of a catadioptric "dry" projection system for comparison purposes;

Fig. 2 shows an illustration of a catadioptric liquid immersion projection lens system according to one embodiment of the present invention;

Fig. 3 shows an illustration of the last optical elements in the optical path of Fig. 2 according to one embodiment of the present invention;

Fig. 4 shows an illustration of the boundary lens, the immersion liquid layer and the image plane;

Fig. 5 shows an illustration of the marginal ray path passing into the last lens element according to one embodiment of the present invention; and

Fig. 6 shows an illustration of the marginal ray path passing through the last lens element into the immersion liquid layer according to one embodiment of the present invention.

Fig. 1 is an illustration of a catadioptric "dry" projection system for comparison purposes, which was disclosed in EP1191378A1. This "dry" projection system includes a first set of field lens elements L11 to L13, a meniscus anastigmat L14 to L17 which aids in correcting aberrations, and a positive powered set of lens elements L18 to L20, which together comprise a first field lens group G1, a beam splitting means FM(1, 2), a Mangin mirror arrangement G2 including two Schupmann lenses L21, L22 and a concave mirror CM which provides an aberration correcting function. The system also includes a positive powered set of lens elements L31 to L33, a negative lens element L34, a positive powered set of lens elements L35 and L39, a negative powered anastigmat L40 which corrects aberrations, and a positive powered lens element L41 which together comprise a second field lens group G3. Light is passed from a reticle R through the first field lens group G1, then through the beam splitter FM(1, 2) to Mangin mirror arrangement G2, and finally through the beam splitter FM(1, 2) and the second field lens group G3. By this arrangement an image may be conveyed from the reticle R to a wafer W with negative magnification so as to controllably expose a photoresist on the wafer.

Figs. 2 and 3 and Tables 1 and 2 show a detailed embodiment of the invention. Light from the object plane OP passes through a plane window E201, a first positive powered group of field lens elements E202 and E203, an anastigmat E204 to E208, adapted to reduce spherical aberration, a second positive powered group of field lens elements E209 to E211, a beam splitter E212 and E218, a catadioptric anastigmat

including two Schupmann lenses E213 and E214 and a concave mirror E215, the beam splitter E212 and E218 for a second time, a third positive powered group of field lens elements E219 to E221, a double-Gauss anastigmat E222 to E225 arranged to reduce spherical aberration, a fourth positive powered group of field lens elements E226 to E232, a boundary lens E233, a layer of immersion liquid IL, and to an image plane IP.

The fourth positive powered group of field lens elements includes a first positive powered lens element E231, and a second positive powered lens element E232. The double-Gauss anastigmat includes a third positive lens element E222, a first negative powered lens element E223, a second negative powered lens element E224, and a fourth positive powered lens element E225.

Although Tables 1 and 2 give specific values for various optical parameters of the optical projection system, it will be appreciated that these are merely examples and it is considered that the optical projection system can be implemented with the parameters for certain optical elements falling within a range of plus or minus 5% from the tabulated finite values, as follows.

The thicknesses of lens elements E222 to E225 and E231 to E233, and the radius of curvatures of optical surfaces S240, S242, S244, S247, S259, S261 and S263 may have values as follows:

The first positive powered lens element E231 has an axial thickness greater than 26.1mm and less than 28.9mm, and an object side surface S259 with an axial radius of curvature greater than 103mm and less than 114mm;

The second positive powered lens element E232 has an axial thickness greater than 26.5mm and less than 29.3mm, and an object side surface S261 with an axial radius of curvature greater than 83.2mm and less than 91.9mm;

The boundary lens E233 has an axial thickness greater than 41.6mm and less than 46.0mm, and an object side surface S263 with an axial radius of curvature greater than 56.9mm and less than 62.9mm;

The third positive powered lens element E222 has an axial thickness greater than 43.9mm and less than 48.5mm, and an object side surface S240 with an axial radius of curvature greater than 128mm and less than 141mm;

The first negative powered lens element E223 has an axial thickness greater than 11.9mm and less than 13.1mm, and an object side surface S242 with an axial radius of curvature greater than 1540mm and less than 1710mm;

The second negative powered lens element E224 has an axial thickness greater than 11.9mm and less than 13.1mm, and an object side surface S244 with an axial radius of

curvature greater than 184mm and less than 204mm; and
The fourth positive powered lens element E225 has an axial thickness greater than 30.6mm and less than 33.9mm, and an image side surface S247 with an axial radius of curvature greater than 189mm and less than 209mm;

More preferably, the ranges of values for the parameters of the optical projection system are within a narrower range of plus or minus 1% of the tabulated finite values. Accordingly the thicknesses of lens elements E222 to E225 and E231 to E233, and the radius of curvatures of optical surfaces S240, S242, S244, S247, S259, S261 and S263 may preferably have values as follows when operating at a wavelength of 157nm:

The first positive powered lens element E231 has an axial thickness greater than 27.22mm and less than 27.77mm, and an object side surface S259 with an axial radius of curvature greater than 107.6mm and less than 109.8mm;

The second positive powered lens element E232 has an axial thickness greater than 27.63mm and less than 28.19mm, and an object side surface S261 with an axial radius of curvature greater than 86.67mm and less than 88.42mm;

The boundary lens E233 has an axial thickness greater than 43.37mm and less than 44.25mm, and an object side surface S263 with an axial radius of curvature greater than 59.27mm and less than 60.46mm;

The third positive powered lens element E222 has an axial thickness greater than 45.71mm and less than 46.63mm, and an object side surface S240 with an axial radius of curvature greater than 133.3mm and less than 136.0mm;

The first negative powered lens element E223 has an axial thickness greater than 12.38mm and less than 12.63mm, and an object side surface S242 with an axial radius of curvature greater than 1608mm and less than 1641mm;

The second negative powered lens element E224 has an axial thickness greater than 12.38mm and less than 12.63mm, and an object side surface S244 with an axial radius of curvature greater than 191.9mm and less than 195.8mm; and

The fourth positive powered lens element E225 has an axial thickness greater than 31.91mm and less than 32.56mm, and an image side surface S247 with an axial radius of curvature greater than 197.4mm and less than 201.3mm.

Even more preferably still, the values of the radius of curvature of the surfaces of the optical elements E201 to E233, and the thicknesses of the optical elements E201 to E233, have values according to Tables 1 and 2.

In Tables 1 and 2 preferred values of the radius of curvature and the axial

distances between optical surfaces of optical elements E210 to E233 are given. As those skilled in the art will appreciate, workable systems may be designed in which all the parameters given in Tables 1 and 2 may be allowed to vary from the specific values given by plus or minus 1 percent, and even up to plus or minus 5 percent with appropriate adaptation. For example when operating at 157nm this would give for surface S263 a radius of curvature greater than 56.9mm and less than 62.9mm, or more preferably greater than 59.27mm and less than 60.46mm, or most preferably 59.8643mm. The values for the radius of curvatures of the curved surfaces of the optical elements E202 to E233 and for the thicknesses and separations of the optical elements E202 to E211, E213 to E215, and E219 to E233 will of course change if the operating wavelength is changed.

An important feature is the presence of a liquid (other than glass) between the image side surfaces S264 of the boundary lens 233 and the image plane IP, both of which may be plane (infinite radius of curvature) as illustrated in Fig. 4. It should be noted that liquids other than water, such as perfluoropolyether, may be used in some embodiments and that the use of the term "liquid" is meant to include any fluid medium other than glass, having a refractive index substantially greater than 1. Suitable liquids include water, (which may be de-ionized and/or degassed) and perfluoropolyethers.

This embodiment of the invention provides improved resolution compared with the dry microlithographic projection system of Figure 1, in which the wafer is immersed in a gas. The wafer is immersed in liquid, which reduces the speed and wavelength of light incident on the photoresist by a factor of about 1.4, without changing the wavelength of the light source. It thereby allows Numerical Apertures (NA) significantly greater than 1.0, by avoiding the total internal reflection of light that would have occurred at the last lens surface if the wafer had been immersed in a gas of refractive index close to 1.0.

The illustrated embodiment provides a specific "wet" catadioptric optical design at NA 1.2, a factor of about 1.4 times higher than "dry" designs at NA 0.85 such as Fig. 1. This disclosed catadioptric design also avoids some of the practical limitations of prior art dioptric "dry" immersion optical designs.

In this system, the theoretical advantages of liquid immersion are realized by means of a catadioptric large-field deep ultraviolet microlithographic projection optical design, whose NA is increased beyond the theoretical limit in air of 1.0, without the lens diameters or surface curvatures increasing beyond practical

fabrication limits, and also without a reduction in field size or spectral bandwidth of light source that would occur with prior art dioptric designs. The "wet" catadioptric NA 1.2 design has a comparable track length (reticle-wafer distance) to a "dry" catadioptric NA 0.85 design, and the same instantaneous wafer field size of 26 x 5 mm and a relatively small increase in lens diameters, which minimizes the changes required in the lithography scanner tool body design, while allowing the same scanned fields to be covered over the wafer.

A catadioptric design is preferred (although it is not essential) because it does not require large separation of negative and positive powered lens elements for field curvature correction. Instead, the field is flattened by means of a concave positive powered mirror (element E215 in Fig. 2 and Tables 1 and 2). Negative powered lens elements close to this mirror (so-called Schupmann lenses, elements E213 and E214 in Fig. 2 and Tables 1 and 2) provide further field curvature correction and sufficient achromatization for the NA to be increased above 1.0 without the need for a second type of refracting material or a reduction in spectral bandwidth. This allows the design to be optimized for existing 0.4 pm bandwidth line-narrowed ArF excimer lasers, using only fused silica lens elements, no calcium fluoride elements, and deionized water of about 1 mm thickness as the immersion medium (IL in Fig. 2 and Tables 1 and 2).

It would be straightforward to re-optimize the disclosed design for use with a line-narrowed KrF laser. The design concept may also be applied to an F2 excimer laser, using only calcium fluoride lens elements with for example a 0.1 mm thickness of perfluoropolyether immersion liquid layer.

Many types of prior art "dry" catadioptric designs have been designed and published by Nikon Corporation and others. However, this invention is most closely related to, but not limited to, what may be described as the "V-type" catadioptric optical design form, which uses V-shaped fold mirrors between two intermediate images. This form has the advantage of relatively small lens diameters and a mechanical package similar to a dioptric lens. It should however be noted that alternatives exist to the V-shaped fold mirror, such as a splitter cube which has an equivalent effect.

In order to operate effectively with liquid immersion between the last lens element surface and the wafer, this last optical surface should preferably be a plane surface (surface S264 in Figs. 2 and 4 and Tables 1 and 2). This facilitates the liquid dynamics during wafer scanning, minimizes the possibility of bubble formation within

the liquid, and minimizes sensitivity to magnification changes with liquid refractive index and dispersion (lateral color), since for a telecentric system in wafer space the chief rays enter the liquid at zero angle of incidence.

In a classical liquid immersion microscope objective, the refractive index difference between the last lens element and liquid introduces spherical aberration, which is minimized by using the least possible thickness of liquid and finding a liquid whose refractive index matches as closely as possible that of the lens element. In the deep-UV microlithography situation, the thickness of the liquid is chosen for other reasons, such as optical transmission, as well as liquid dynamics and mechanical considerations during wafer scanning and stepping. This design is not constrained by the choice of liquid thickness or refractive index. Currently, a liquid thickness of 1 mm is assumed, but the optical design may easily be re-optimized for a different thickness or liquid refractive index. Again this is facilitated by having a plane last lens surface next to the liquid, when the spherical aberration is constant across a large field size, and can be easily corrected at a pupil plane in the system by means of at least one aspheric surface.

In this invention, neither the aplanatic nor concentric conditions are used in the last element, i.e., boundary lens, next to the wafer (surface S263 on element E233, Figs. 2 and 4). In this case, the marginal ray convergence angle is slightly smaller inside element 233 than it was prior to entering it (as seen in Figs. 5 and 6). This feature has three advantages:

a. The D/R (clear diameter/radius of curvature) of this surface can be constrained to be <1.5, which is within normal optical polishing techniques for large, high quality, optical elements.

b. The resulting spherical aberration and coma may easily be corrected in other elements in the system, including several aspherical surfaces, which is advantageous in the correction of high-order aberrations that change rapidly across the wide field used in microlithography, such as oblique spherical aberration, coma, astigmatism and distortion. This strategy is particularly effective in a long, complex, system with two intermediate images, such as the V-type catadioptric design.

c. There is no focused ghost image on the wafer surface, as would occur with an exactly concentric surface.

Classical microscope objectives also employ at least one element before the last one that has a combination of aplanatic and concentric surfaces. The preferred embodiment of the invention employs, instead, at least two positive meniscus

elements before the last one (elements E231 and E232 in Figs. 2 and 3 and Tables 1 and 2) whose surfaces are neither exactly concentric nor aplanatic, so as to avoid both extreme curvatures and extreme angles of incidence near or beyond the critical angle.

At least one of these surfaces may be aspheric, so as to perform similar aberration correction functions to those which in lower NA "dry" designs may be achieved with air spaces between adjacent elements (e.g. the airspace between elements E230 and E231 in Fig. 2).

The relatively high optical power in the last three positive elements minimizes the size increase of lens elements required in the rest of the system as the "dry" NA of 0.85 in designs such as Fig. 1 is increased to a "wet" NA of 1.2. This is very advantageous because the lenses would otherwise be larger than can be readily made with existing technology, and would thus be exceptionally expensive. The relatively high power of the last three elements also allows a pupil (aperture stop) position closer to the wafer than is typical in "dry" designs, e.g. Fig. 1.

In the prior art, a common feature of a catadioptric “dry” lithography projection system included a negative powered element between the pupil and wafer. This feature which is used to correct aberrations has the disadvantage that in a “wet” catadioptric optical projection system the main positive powered lenses would have to be larger than otherwise. The new arrangement in the present application has the advantage that it does not require such a negative powered lens and this further minimizes the lens diameter of the main positive powered lenses, and also the length of the optical path. The aberration correction of a negative lens element in "dry" designs (e.g. element L38 in Fig. 1) is performed, instead, by an aspheric surface close to the pupil.

The negative powered lens group, elements E222 to E225 in Fig. 2, is a double-Gauss anastigmat arranged to reduce spherical aberration. It contributes to field curvature and lateral color correction in the overall design, while minimizing higher-order coma and oblique spherical aberration that would otherwise be larger at NA 1.2 than they were in "dry" designs at NA 0.85 (Fig. 1). This feature provides the advantage of allowing a wider field of view than would otherwise be possible at NA 1.2.

As illustrated in Figs. 5 and 6, it can be seen that the angle L of the marginal ray of the light cone projected to the boundary lens E233 decreases on passing into the boundary lens E233.

Fig. 5 and Fig. 6 illustrates one embodiment, where it can be seen that the geometric focus F of the marginal rays L, prior to entering the boundary lens E233, is

located between the two optical surfaces S263 and S564 of the boundary lens, and is also between the centre of curvature CC of the boundary lens and the optical surface S263 of the boundary lens.

As also can be seen from Fig. 6, as the refractive index of the boundary lens E233 may typically not be equal to, and practically would be higher than, the refractive index of the layer of immersion liquid IL, the angle S of the marginal ray may increase on passing from the boundary lens E233 to the immersion liquid layer before impinging on the image plane IP.

It should be noted that the terms "object plane", "image plane", "pupil plane", and "plane mirror" are not limited to being plane surfaces, or plane mathematical surfaces, but may also be curved physical or mathematical surfaces. It should also be noted that the illustrations in Figures 1 to 6 are not to scale, and that the beam splitter E212, E218 may be a single element having two optical paths there through.

The aspheric surfaces A(1) to A12) in Table 1 are defined by the equation:

$$Z = \frac{(CURV)Y^2}{1+(1-(1+K)(CURV)^2Y^2)^{1/2}} + (A)Y^4 + (B)Y^6 + (C)Y^8 + (D)Y^{10} + (E)Y^{12} + (F)Y^{14} + (G)Y^{16} + (H)Y^{18} + (J)Y^{20}$$

The values A, B, C, D, E, F, G, H, and J are tabulated in Table 2.

In Table 1, the sign of the radius indicates the direction of curvature, CC indicates a concave surface and CX indicates a convex surface. In the embodiment of table 1 the largest diameter of any of the lens elements E202 to E211, E213 to 217, E219 to E228 and E229 to E233 is only 242.8mm for the positive lens element 227.

Table 1.

Element	Radius of Curvature		Axial distance to next surface	
	Back	Front	Back	Front
E201	Infinity	Infinity	8.0000	1.0000
E202	296.2214 CX	-960.8207 CX	29.0933	1.0000
E203	29.3195 CX	219.1233 CC	31.5402	69.4729
E204	105.2542 CX	433.274 A(1)	30.2818	1.1583
E205	77.5810 CX	85.0063 CC	35.9523	30.5076
E206	-101.0777 CC	-109.0575 CX	50.0000	22.2382
E207	-86.9124 CC	-277.5585 CX	17.0119	14.1315
E208	-313.0101 CC	-121.4285 CX	47.1365	1.0000
E209	244.5825 A(2)	-150.1716 CX	43.8716	1.0000
E210	287.8659 CX	-1006.7736 CX	33.3703	3.9387
E211	232.1539 CX	3443.7633 A(3)	26.1499	64.9981
E212	Infinity		-248.6029	
E213	99.3337 A(4)	760.1855 CX	-12.5000	-41.6713
E214	112.9332 CC	210.0532 CX	-12.5000	-23.5805
E215	150.9146 CC		23.5805	
E216	210.0532 CX	112.9332 CC	12.5000	41.6713
E217	760.1855 CX	99.3337 A(5)	12.5000	248.6029
E218	Infinity		-64.0489	
E219	3037.9516 CC	252.1281 CX	-26.2012	-1.0000
E220	-422.2688 CX	878.8560 CX	-28.0789	-1.0000
E221	-197.8858 CX	-1895.1173 CC	-36.9167	-1.0000
E222	-134.6900 CX	221.3134 A(6)	-46.1691	-18.4179
E223	-1624.3296 CX	89.3372 A(7)	-12.5000	-44.5981
E224	193.8597 CC	211.4093 A(8)	-12.5000	-14.8193
E225	-1550.8977 CX	199.3485 CX	-32.2367	-85.9268
E226	1142.6351 A(9)	305.6765 CX	-26.7479	-1.0002
E227	-341.9216 CX	-5217.2118 CC	-30.8753	-1.0000
E228	-274.1211 CX	3414.1345 A(10)	-33.1045	-9.8682
AS	Infinity		5.3722	
E229	-337.4484 CX	-6051.4400 CC	-40.2177	-1.0007
E230	-286.9832 CX	-47776.7480 CC	-29.3234	-1.0000
E231	-108.7000 CX	152.1155 A(11)	-27.4984	-1.0000
E232	-87.5448 CX	167.7647 A(12)	-27.9141	-1.0000
E233	-59.8643 CX	Infinity	-43.8105	
IL	Infinity	Infinity	-1.0000	

Table 2.

Aspheric	Curv	K E	A F	B G	C H	D J
A (1)	0.00230801	0.000000 1.24264E-23	1.35800E-07 0.00000E+00	4.43804E-13 0.00000E+00	5.17522E-16 0.00000E+00	-2.13416E-20 0.00000E+00
A (2)	-0.00408861	0.000000 5.62462E-26	-2.93564E-09 -1.64835E-30	3.96730E-13 0.00000E+00	-3.34166E-17 0.00000E+00	-3.22241E-22 0.00000E+00
A (3)	0.00029038	0.000000 -2.36540E-26	2.58800E-08 4.15511E-31	-1.30225E-14 0.00000E+00	-1.33600E-17 0.00000E+00	7.99491E-22 0.00000E+00
A (4)	0.01006708	0.000000 -2.27561E-26	-7.39601E-08 -3.78485E-28	-3.15605E-12 0.00000E+00	-2.13807E-16 0.00000E+00	-1.63643E-20 0.00000E+00
A (5)	0.01006708	0.000000 -2.27561E-26	-7.39601E-08 -3.78485E-28	-3.15605E-12 0.00000E+00	-2.13807E-16 0.00000E+00	-1.63643E-20 0.00000E+00
A (6)	-0.00451848	0.000000 -1.21801E-25	4.41668E-09 -1.34613E-30	-5.79647E-13 0.00000E+00	-2.25277E-17 0.00000E+00	6.73716E-22 0.00000E+00
A (7)	-0.01119354	0.000000 -2.48878E-24	-6.93411E-08 -1.79947E-28	-3.30971E-12 0.00000E+00	-3.11788E-16 0.00000E+00	-2.65850E-20 0.00000E+00
A (8)	-0.00473016	0.000000 1.16802E-24	-4.72629E-08 -3.23662E-29	6.08755E-12 0.00000E+00	-1.63469E-16 0.00000E+00	-2.65475E-20 0.00000E+00
A (9)	0.00087517	0.000000 3.68761E-26	1.10141E-08 2.41555E-31	-5.01692E-13 0.00000E+00	-2.00493E-17 0.00000E+00	-8.25872E-22 0.00000E+00
A (10)	-0.00029290	0.000000 -3.84229E-26	-6.20015E-09 2.58938E-31	-1.26050E-13 0.00000E+00	-3.59314E-17 0.00000E+00	1.65781E-21 0.00000E+00
A (11)	-0.00657395	0.000000 9.31381E-25	3.58357E-08 5.59854E-28	-7.83628E-12 0.00000E+00	7.69481E-16 0.00000E+00	-7.68364E-20 0.00000E+00
A (12)	-0.00596073	0.000000 -6.00362E-23	-1.91466E-07 -8.48073E-28	4.589321E-12 0.00000E+00	1.26164E-15 0.00000E+00	4.61975E-19 0.00000E+00

Claims:

1. An optical system for projecting an image of an object plane (OP) onto an image plane (IP) comprising:
a boundary lens (E233); and
at least one layer of immersion liquid (IL) between the boundary lens (E233) and the image plane (IP);
said boundary lens (E233) having an object side optical surface (S263) shaped such that for light projected onto the image plane (IP) through the boundary lens (E233) the marginal ray convergence angle (L) prior to incidence is larger than the marginal ray convergence angle (S) within said boundary lens (E233).

2. The optical projection system of claim 1 further comprising:
at least one positive powered lens element (E231, E232) proximal to said boundary lens (E233), and having an aspheric optical surface (S259, S260, S261, S262).

3. The optical projection system of claim 1 wherein there are provided:
a first positive powered lens element (E231) proximal to said boundary lens (E233), and having at least one aspheric optical surface (S259, S260); and
a second positive powered lens element (E232) between the first positive powered lens element (E231) and said boundary lens (E233), and having at least one aspheric optical surface (S261, S262).

4. The optical projection system of claim 3 wherein:
the first positive powered lens element (E231) has an axial thickness greater than 26.1mm and less than 28.9mm, and an object side surface (S259) with an axial radius of curvature greater than 103mm and less than 114mm;
the second positive powered lens element (E232) has an axial thickness greater than 26.5mm and less than 29.3mm, and an object side surface (S261) with an axial radius of curvature greater than 83.2mm and less than 91.9mm; and
the boundary lens (E233) has an axial thickness greater than 41.6mm and less than 46.0mm, and an object side surface (S263) with an axial radius of curvature greater than 56.9mm and less than 62.9mm.

5. The optical projection system of claim 3 wherein: the first positive powered lens element (E231) has an axial thickness greater than 27.22mm and less than 27.77mm, and an object side surface (S259) with an axial radius of curvature greater than 107.6mm and less than 109.8mm; the second positive powered lens element (E232) has an axial thickness greater than 27.63mm and less than 28.19mm, and an object side surface (S261) with an axial radius of curvature greater than 86.67mm and less than 88.42mm; and the boundary lens (E233) has an axial thickness greater than 43.37mm and less than 44.25mm, and an object side surface (S263) with an axial radius of curvature greater than 59.27mm and less than 60.46mm.

6. The optical projection system of any one of claims 1 to 5 further comprising a double-Gauss anastigmat arranged to reduce spherical aberration including a third positive powered lens element (E222), a first negative powered lens element (E223), a second negative powered lens element (E224), and a fourth positive powered lens element (E225).

7. The optical projection system of claim 6 wherein: the third positive powered lens element (E222) has an axial thickness greater than 43.9mm and less than 48.5mm, and an object side surface (S240) with an axial radius of curvature greater than 128mm and less than 141mm; the first negative powered lens element (E223) has an axial thickness greater than 11.9mm and less than 13.1mm, and an object side surface (S242) with an axial radius of curvature greater than 1540mm and less than 1710mm; the second negative powered lens element (E224) has an axial thickness greater than 11.9mm and less than 13.1mm, and an object side surface (S244) with an axial radius of curvature greater than 184mm and less than 204mm; and the fourth positive powered lens element (E225) has an axial thickness greater than 30.6mm and less than 33.9mm, and an image side surface (S247) with an axial radius of curvature greater than 189mm and less than 209mm.

8. The optical projection system of claim 6 wherein: the third positive powered lens element (E222) has an axial thickness greater than 45.71mm and less than 46.63mm, and an object side surface (S240) with an axial radius of curvature greater than 133.3mm and less than 136.0mm;

the first negative powered lens element (E223) has an axial thickness greater than 12.38mm and less than 12.63mm, and an object side surface (S242) with an axial radius of curvature greater than 1608mm and less than 1641mm;
the second negative powered lens element (E224) has an axial thickness greater than 12.38mm and less than 12.63mm, and an object side surface (S244) with an axial radius of curvature greater than 191.9mm and less than 195.8mm; and
the fourth positive powered lens element (E225) has an axial thickness greater than 31.91mm and less than 32.56mm, and an image side surface (S247) with an axial radius of curvature greater than 197.4mm and less than 201.3mm.

9. The optical projection system of any one of claims 1 to 8 further comprising a catadioptric anastigmat comprising a concave mirror (E215) and at least one negative powered Shupmann lens (E213, E214).

10. The optical projection system of claim 9 wherein the catadioptric anastigmat comprises two negative powered Shupmann lenses (E213, E214).

11. The optical projection system of any one of claims 1 to 10 adapted for use with ultraviolet light.

12. An optical projection system for projecting from an object plane (OP) to an image plane (IP) comprising:
an optical system;
a boundary lens (E233); and
at least one layer of immersion liquid (IL) between said boundary lens (E233) and said image plane (IP); wherein
light from the object plane (OP) is transmitted through the optical system, and output with a predetermined marginal ray convergence angle (L); and
said boundary lens (E233) is positioned to receive said light output from the optical system, and adapted such that for light projected onto the image plane (IP) through the boundary lens (E233) the marginal ray convergence angle (L) prior to incidence is larger than the marginal ray convergence angle (S) within said boundary lens (E233).

13. The optical projection system according to claim 12 wherein the optical system comprises;

at least one positive powered lens element (E231, E232) proximal to said boundary lens (E233), and having an aspheric optical surface (S259, S260, S261, S262).

14. The optical projection system of claim 12 wherein the optical system comprises;
a first positive powered lens element (E231) proximal to said boundary lens (E233), and having at least one aspheric optical surface (S259, S260); and
a second positive powered lens element (E232) between the first positive powered lens element (E231) and said boundary lens (E233), and having at least one aspheric optical surface (S261, S262).

15. The optical projection system of claim 14 wherein:
the first positive powered lens element (E231) has an axial thickness greater than 26.1mm and less than 28.9mm, and an object side surface (S259) with an axial radius of curvature greater than 103mm and less than 114mm;
the second positive powered lens element (E232) has an axial thickness greater than 26.5mm and less than 29.3mm, and an object side surface (S261) with an axial radius of curvature greater than 83.2mm and less than 91.9mm; and
the boundary lens (E233) has an axial thickness greater than 41.6mm and less than 46.0mm, and an object side surface (S263) with an axial radius of curvature greater than 56.9mm and less than 62.9mm.

16. The optical projection system of claim 14 wherein:
the first positive powered lens element (E231) has an axial thickness greater than 27.22mm and less than 27.77mm, and an object side surface (S259) with an axial radius of curvature greater than 107.6mm and less than 109.8mm;
the second positive powered lens element (E232) has an axial thickness greater than 27.63mm and less than 28.19mm, and an object side surface (S261) with an axial radius of curvature greater than 86.67mm and less than 88.42mm; and
the boundary lens (E233) has an axial thickness greater than 43.37mm and less than 44.25mm, and an object side surface (S263) with an axial radius of curvature greater than 59.27mm and less than 60.46mm.

17. The optical projection system of any one of claims 12 to 16 wherein the optical system comprises;

a double-Gauss anastigmat arranged to reduce spherical aberration including a third positive powered lens element (E222), a first negative powered lens element (E223), a second negative powered lens element (E224), and a fourth positive powered lens element (E225).

18. The optical projection system of claim 17 wherein:
the third positive powered lens element (E222) has an axial thickness greater than 43.9mm and less than 48.5mm, and an object side surface (S240) with an axial radius of curvature greater than 128mm and less than 141mm;
the first negative powered lens element (E223) has an axial thickness greater than 13.111.9mm and less than 11.913.1mm, and an object side surface (S242) with an axial radius of curvature greater than 1540mm and less than 1710mm;
the second negative powered lens element (E224) has an axial thickness greater than 13.111.9mm and less than 11.913.1mm, and an object side surface (S244) with an axial radius of curvature greater than 184mm and less than 204mm; and
the fourth positive powered lens element (E225) has an axial thickness greater than 30.6mm and less than 33.9mm, and an image side surface (S247) with an axial radius of curvature greater than 189mm and less than 209mm.

19. The optical projection system of claim 17 wherein:
the third positive powered lens element (E222) has an axial thickness greater than 45.71mm and less than 46.63mm, and an object side surface (S240) with an axial radius of curvature greater than 133.3mm and less than 136.0mm;
the first negative powered lens element (E223) has an axial thickness greater than 12.38mm and less than 12.63mm, and an object side surface (S242) with an axial radius of curvature greater than 1608mm and less than 1641mm;
the second negative powered lens element (E224) has an axial thickness greater than 12.38mm and less than 12.63mm, and an object side surface (S244) with an axial radius of curvature greater than 191.9mm and less than 195.8mm; and
the fourth positive powered lens element (E225) has an axial thickness greater than 31.91mm and less than 32.56mm, and an image side surface (S247) with an axial radius of curvature greater than 197.4mm and less than 201.3mm.

20. The optical projection system of any one of claims 12 to 19 wherein the optical system further comprises a catadioptric anastigmat comprising a concave mirror

(E215) and at least one negative powered Shupmann lens (E213, E214).

21. The optical projection system of claim 20 wherein the catadioptric anastigmat comprises two negative powered Shupmann lenses (E213, E214).

22. The optical projection system of any one of claims 12 to 21 adapted for use with ultraviolet light.

23. A method of projecting onto an image plane (IP) including the steps of:
passing light having a first marginal ray convergence angle (L) to a boundary lens (E233);
passing light having a second marginal ray convergence angle (S) though the boundary lens (E233); and
passing light from said boundary lens (E233) through a layer of immersion liquid (IL) to the image plane (IP); wherein
the first marginal ray convergence angle (L) is greater than the second marginal ray convergence angle (S).

24. The projection method of claim 23 including the step of passing light through at least one positive powered lens element (E231, E232) proximal to said boundary lens (E233), and having an aspheric optical surface (S259, S260, S261, S262).

25. The projection method of claim 23 including the steps of:
passing light through a first positive powered lens element (E231) proximal to said boundary lens (E233), and having at least one aspheric optical surface (S259, S260); and
passing light through a second positive powered lens element (E232) between the first positive powered lens element (E231) and said boundary lens (E233), and having at least one aspheric optical surface (S261, S262).

26. The projection method of claim 25 including the steps of:
passing light through the first positive powered lens element (E231) having an axial thickness greater than 26.1mm and less than 28.9mm, and an object side surface (S259) with an axial radius of curvature greater than 103mm and less than 114mm;
passing light through the second positive powered lens element (E232) having an axial

thickness greater than 26.5mm and less than 29.3mm, and an object side surface (S261) with an axial radius of curvature greater than 83.2mm and less than 91.9mm; and

passing light through the boundary lens (E233) having an axial thickness greater than 41.6mm and less than 46.0mm, and an object side surface (S263) with an axial radius of curvature greater than 56.9mm and less than 62.9mm.

27. The projection method of claim 25 including the steps of:
passing light through the first positive powered lens element (E231) having an axial thickness greater than 27.22mm and less than 27.77mm, and an object side surface (S259) with an axial radius of curvature greater than 107.6mm and less than 109.8mm;
passing light through the second positive powered lens element (E232) having an axial thickness greater than 27.63mm and less than 28.19mm, and an object side surface (S261) with an axial radius of curvature greater than 86.67mm and less than 88.42mm; and
passing light through the boundary lens (E233) having an axial thickness greater than 43.37mm and less than 44.25mm, and an object side surface (S263) with an axial radius of curvature greater than 59.27mm and less than 60.46mm.

28. The projection method of any one of claims 23 to 27 further including the step of passing light through a double-Gauss anastigmat arranged to reduce spherical aberration including a third positive powered lens element (E222), a first negative powered lens element (E223), a second negative powered lens element (E224), and a fourth positive powered lens element (E225).

29. The projection method of claim 28 including the steps of:
passing light through the third positive powered lens element (E222) having an axial thickness greater than 43.9mm and less than 48.5mm, and an object side surface (S240) with an axial radius of curvature greater than 128mm and less than 141mm;
passing light through the first negative powered lens element (E223) having an axial thickness greater than 11.9mm and less than 13.1mm, and an object side surface (S242) with an axial radius of curvature greater than 1540mm and less than 1710mm;
passing light through the second negative powered lens element (E224) having an axial thickness greater than 11.9mm and less than 13.1mm, and an object side surface (S244) with an axial radius of curvature greater than 184mm and less than 204mm;

and
passing light through the fourth positive powered lens element (E225) has having axial thickness greater than 30.6mm and less than 33.9mm, and an image side surface (S247) with an axial radius of curvature greater than 189mm and less than 209mm.

30. The projection method of claim 28 including the steps of:
passing light through the third positive powered lens element (E222) having an axial thickness greater than 45.71mm and less than 46.63mm, and an object side surface (S240) with an axial radius of curvature greater than 133.3mm and less than 136.0mm;
passing light through the first negative powered lens element (E223) having an axial thickness greater than 12.38mm and less than 12.63mm, and an object side surface (S242) with an axial radius of curvature greater than 1608mm and less than 1641mm;
passing light through the second negative powered lens element (E224) has an axial thickness greater than 12.38mm and less than 12.63mm, and an object side surface (S244) with an axial radius of curvature greater than 191.9mm and less than 195.8mm;
and
passing light through the fourth positive powered lens element (E225) has an axial thickness greater than 31.91mm and less than 32.56mm, and an image surface (S247) with an axial radius of curvature greater than 197.4mm and less than 201.3mm.

31. The projection method of any one of claims 23 to 30 including the step of passing light through a catadioptric anastigmat comprising a concave mirror (E215) and at least one negative powered Shupmann lens (E213, E214).

32. The projection method of claims 31 including the step of passing light through two negative powered Shupmann lens (E213, E214).

33. The projection method of any one of claims 23 to 32 wherein said light is a beam of ultraviolet light.

Abstract

Optical Projection System for Photolithography

A lithographic immersion projection system for projecting an image at high resolution over a wide field of view. The projection system includes a final lens which decreases the marginal ray angle of the optical path before it passes into the immersion liquid to impinge on the image plane.

Fig. 2

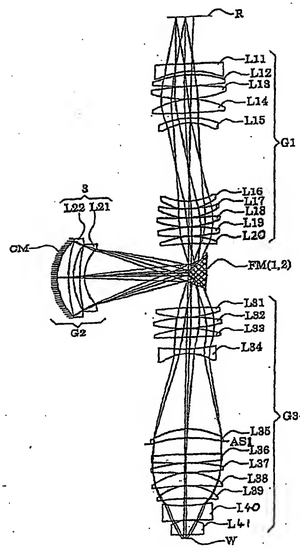
R
L11
L12
L13
L14
L15
G1
L16
L17
L18
L19
L20
3
L22 L21
CM
FM(1,2)
G2
L31
L32
L33
L34
G3
L35
AS1
L36
L37
L38
L39
L40
L41
W

Fig. 1

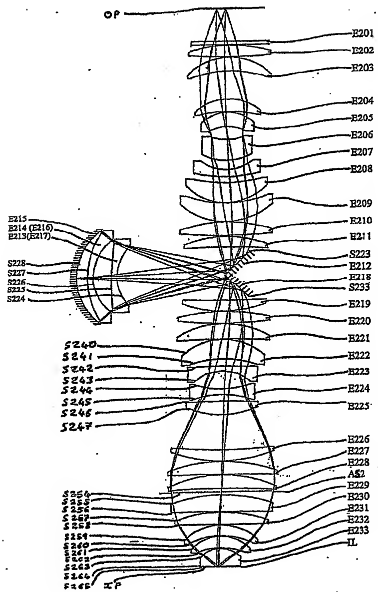
OP
E201
E202
E203
E204
E205
E206
E207
E208
E209
E210
E211
S223
E212
E218
S233
E219
E220
E221
E222
E223
E224
E225
E226
E227
E228
AS2
E229
E230
E231
E232
E233
IL
E215
E214 (E216)
E213(E217)
S228
S227
S226
S225
S224
S240
S241
S242
S243
S244
S245
S246
S247
S254
S255
S256
S257
S258
S259
S260
S261
S262
S263
S264
S265
IP

Fig. 2

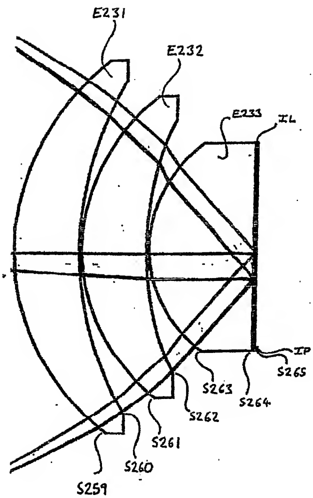

Fig. 3

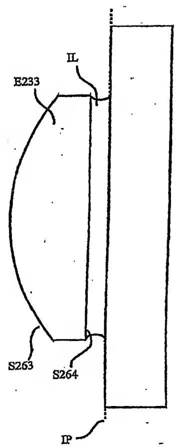

Fig. 4

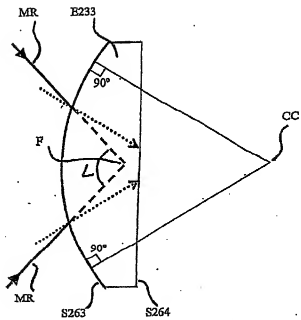

Fig. 5

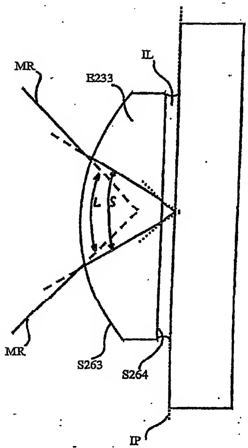

Fig. 6